**Development of an energy-efficient cooling system based on the magnetocaloric effect**

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**Abstract.** This article focuses on the development of an energy-efficient cooling system based on the magnetocaloric effect. Considering that this technology, which operates by changing the temperature of materials under the influence of a magnetic field, offers higher energy efficiency, environmental friendliness, and lower noise levels compared to traditional cooling methods, magnetocaloric materials based on manganese pnictides were analyzed. The structure, magnetic properties, and phase stability of these materials were studied in detail. The parameters of magnetic entropy change and relative cooling power were calculated using Newton-Maxwell equations for a sample in which issues such as hysteresis, phase stability, and the influence of doping elements were addressed. According to the research results, the proposed manganese pnictide material demonstrates high magnetocaloric efficiency and can be utilized in modern energy-saving cooling systems.

**INTRODUCTION**

The phenomenon of the magnetocaloric effect (ME) is understood as the process of changing the temperature or entropy of a material under the influence of a magnetic field, with the highest value observed around the phase transition temperature. In magnetic systems based on the ME phenomenon, when an external magnetic field is applied, the magnetic moments of the material are aligned, the entropy decreases, and the material heats up. Conversely, when the magnetic field is removed, the order of magnetic moments is disrupted, and the material cools due to an increase in entropy. This physical process forms the basis of magnetic field cooling technology.

Magnetocaloric materials are preferable to conventional cooling systems due to their high energy efficiency, refrigerant-free operation, low noise levels, and long service life. Currently, research conducted worldwide is focused on the development of materials such as ferromagnetic alloys, Heusler alloys, as well as manganese pnictides and their modifications. Significant changes in magnetic entropy during magnetic phase transitions observed in manganese pnictides allow for expanding the cooling range, leading to increased scientific and practical interest in these materials.

Currently, the modern applications of ME are expanding. It is important not only for creating environmentally friendly, freon-free magnetic cooling systems for household refrigerators and air conditioners but also as a promising solution for highly sensitive sensors, infrared equipment, magnetic resonance imaging systems, and cooling of scientific equipment operating in high magnetic fields.

Phase transitions arising from magnetic phase (MF) transitions, associated with the ordering of magnetic moments characteristic of the manganese pnictide group, contribute to achieving high results in the magnetocaloric effect. Manganese pnictides possess a strong magnetic structure, allowing them to have a wide range of flexible temperatures between 250-350 K, low hysteresis, a stable crystalline structure, and the ability to maintain parameters during thermal cycles. Moreover, due to their environmental friendliness, low cost, and high cooling and thermodynamic efficiency, they can be considered one of the most promising materials for new generation magnetic cooling systems.

Despite the rapid development of materials technology based on magnetocaloric effects (MEs) in recent years, there are a number of unresolved scientific problems limiting their widespread practical application, namely hysteresis, phase stability, and the influence of alloying elements. The magnetic-phase transitions characteristic of manganese pnictides and their thermodynamic properties play an important role in solving these problems.

The strong magnetocaloric effect is usually associated with first-order magnetic phase transitions. The formation of hysteresis, which can reach up to 3-10 K, causes energy losses in thermodynamic cycles. This is due to the fact that such transitions are often accompanied by deformation of the structure or redistribution of atomic lattices, which reduces the efficiency of the magnetocaloric effect (MCE), worsens the frequency of magnetic entropy changes, and diminishes the energy efficiency of the cooling cycle. Therefore, the minimization of hysteresis is one of the most urgent scientific tasks in the technology of magnetocaloric materials.

The composition of magnetic phase transitions in manganese pnictides exhibits high sensitivity to changes in atomic lattice parameters and temperature. In this context, the high temperature sensitivity of magnetic ordering complicates the structural stability under cyclic operation conditions of materials. This results in insufficient phase stability, leading to a decrease in magnetic entropy value over cycles, degradation of magnetic properties, and disruption of structural equilibrium.

To optimize the magnetocaloric properties of manganese pnictides, doping is carried out using elements such as Fe, Si, Ge, Co, Ni, V, and Cr. However, such additives cause structural disruption by altering the phase transition temperature, increase hysteresis due to enhanced magnetic moment, and create phase imbalance by changing the atomic lattice parameters.

It is possible to address these issues by increasing magnetocaloric efficiency through hysteresis reduction, ensuring long-term cyclic operation of materials by providing phase stability, achieving precise adjustment of Curie temperature and magnetic entropy values through appropriate selection of additives, and developing magnetocaloric materials into a competitive alternative to existing cooling systems.

In this article, we will analyze magnetocaloric materials based on manganese pnictides with a new composition, study their crystal structure, phase stability, and magnetic properties, and develop recommendations for new cooling systems based on them.

**EXPERIMENTAL RESEARCH**

Since the magnetic and structural properties of magnetocaloric materials based on manganese pnictides are highly dependent on their production technology, the use of various methods, such as arc melting, spark plasma treatment, and mechanical alloying, plays a key role in ensuring the homogeneity of the material's composition, structure, and phase stability.

Based on the study of the aforementioned methods of obtaining alloys, a comparative table of advantages and disadvantages was developed, enabling the determination of which methods can be used to achieve high-quality results in alloy production.

**Table 1.** Comparative table of methods for obtaining alloys

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| No | Method | Advantage | Disadvantage | Effective  (\*doped) | | | |
| MnAs | MnP | MnFePAs | MnTX |
| 1. | Arc melting | Fast, simple, combines compositions by melting | Evaporation of pnictides |  |  |  |  |
| 2. | Spark plasma treatment | Very high homogeneity and density | Special equipment required |  |  |  |  |
| 3. | Mechanical alloying | Atomic level mixing | Probability of amorphization |  |  | \* | \* |

Structural stability, phase homogeneity, and magnetocaloric properties in alloys based on manganese pnictides depend on thermal treatment, particularly the hardening process. In materials obtained by arc melting, spark plasma treatment, and mechanical doping, where the distribution of atoms and phase composition are not fully formed, hardening serves to achieve a balanced state of the atomic lattice, uniform distribution of doping elements, elimination of mechanical stresses in the microstructure and deviations from the ideal crystal lattice structure, increased phase stability, improved ordering of magnetic moments, reduced hysteresis, and optimized parameters of magnetic entropy and energy efficiency. Additionally, by annealing the alloy in a vacuum or inert medium at 650-750°C for 10-24 hours at a moderate temperature, it is possible to achieve complete formation of the material structure, reduce atomic substitution, and stabilize the magnetocaloric properties.

The change in magnetic entropy in the quantitative assessment of magnetocaloric effects characterizes the magnetic phase transitions in the material, the dynamics of magnetic ordering, and the heat exchange capacity during the magnetic cooling process. Its value is determined using the following expression:

(1)

where temperature points; points of the magnetic field; magnetization value.

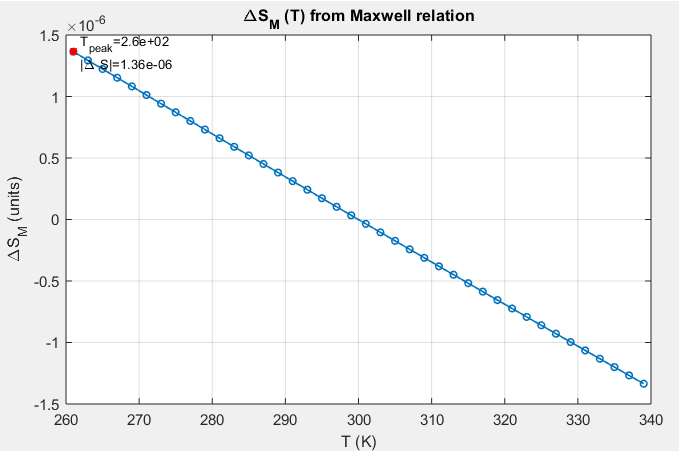
When assessing the actual effectiveness of materials based on ME in practice, the change in magnetic entropy alone is not sufficient. Another important parameter in a magnetic cooling system is the relative cooling power. This parameter provides a quantitative assessment of how much heat the material can transfer during the cooling cycle and is determined as follows:

(2)

where is the maximum value of magnetic entropy change, and is the width at a height equal to half the peak point .

According to expression (2), the greater the value of , the higher the magnetocaloric effect of the material. A wide range of δT ensures the material's ability to work effectively across a broad range of thermal temperatures. In other words, the relative cooling power is the main parameter characterizing the useful working capacity of the material during periodic operation. In modern materials, RCP is typically in the range of RCP>400-500 J/kg.

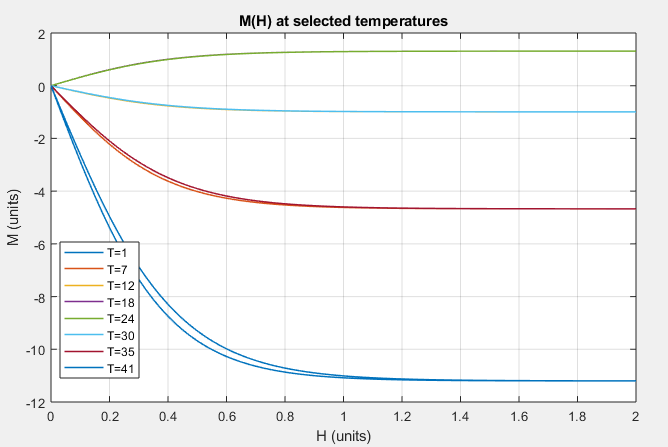
Using expression (1) derived from Maxwell's equation, we construct temperature curves for (Figure 1).



**FIGURE 1.** Temperature dependence of magnetic entropy change calculated using Maxwell's equation

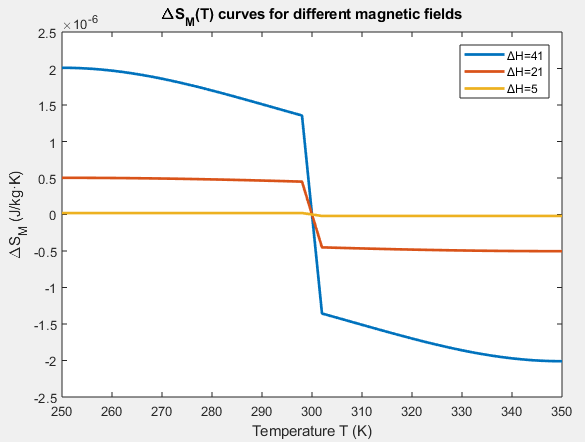
According to the obtained graph, at a certain temperature, a sharp change in the magnetic order occurs at the point of magnetic phase transition. This leads to an increase in the magnetic flux density in the material at this temperature, as well as a decrease in the magnetic flux density depending on the temperature, significantly reducing the magnetization of the material compared to the temperature. Additionally, the determined values and are important quantities for assessing the magnetocaloric efficiency, which substantiates the magnetocaloric effect of the manganese pnictide-based alloy and its wide application in magnetic cooling technologies.

To analyze the dependence of magnetization on the magnetic field strength at different temperatures, which directly affect the value of , M(H) curves were constructed (Fig. 2). From the obtained graph, it can be seen that when the temperature is in the range of 1-7 K, the magnetization in the material is high and in a negative direction, and its value changes very quickly under the influence of the magnetic field strength. When the temperature is in the range of 30-41 K, the magnetization value practically does not change. Furthermore, in the temperature range of 18-24 K, a transition state from ferromagnetic to paramagnetic is observed in the material, and it is precisely this phase transition point that is considered crucial in assessing the efficiency of the material's ME.



**FIGURE 2.** Curves of the dependence of magnetization on magnetic field strength at different temperatures

To assess the temperature dependence of the change in magnetic entropy at different values of magnetic field strength, we construct a curve (Fig. 3). According to the analysis of the curves on the obtained graph, a sharp change around T≈300K indicates the presence of a phase transition in the material (since the maximum value of the magnetocaloric effect usually manifests itself near the temperature of the phase transition), as well as an increase in the amplitude of the change in magnetic entropy with increasing magnetic field strength, which indicates a strong dependence of the magnetic ordering of the material on the external field.



**FIGURE 3.** Temperature dependence curves of magnetic entropy change at various values of magnetic field strength m

**RESEARCH RESULTS AND CONCLUSION**

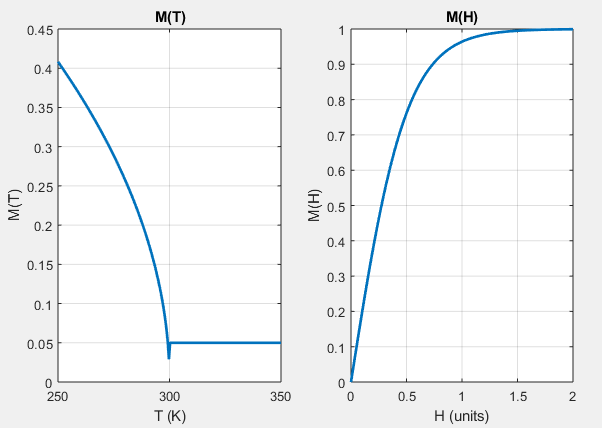
As a result of the conducted research and studies, we will use the methods described above to test a sample of the material used for the energy-efficient cooling system based on the developed ME. We will also evaluate how much heat this sample can transfer during the cooling cycle.

|  |  |  |  |
| --- | --- | --- | --- |
|  | |  | |
| a) | b) | |

**FIGURE 4.** Temperature dependence curves of magnetic entropy for the sample: a) Continuous curve - calculated using Maxwell's equation; b) Continuous curve - experimentally determined, discontinuous curve - results calculated for a certain induction value.

According to the obtained curves, we can observe that the ΔS(T) curves, calculated based on Maxwell's equation, show a sharp increase in the change of magnetic entropy around the material's phase transition temperature. ΔS(T) has a maximum amplitude, which reflects the true value of the magnetocaloric effect (ME). The ΔS taken for a certain value of induction, although small in amplitude, has the same shape around the Curie temperature, and the magnetic ordering of the material strongly depends on temperature.

To determine the effectiveness of the developed magnetocaloric material compared to existing cooling systems, we create curves representing the dependence of magnetization on temperature and magnetic field strength.



**FIGURE 5.** Magnetization curves for temperature and magnetic field strength

Analysis of the obtained curves showed that the developed material has ferromagnetic properties, in which a ferromagnetic-paramagnetic phase transition occurs at a temperature of about 300 K. The material exhibits rapid ordering under the influence of a magnetic field and achieves magnetic saturation under the influence of a high magnetic field strength. Additionally, the developed sample reaches a maximum near the phase transition temperature.

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**REFERENCES**

1. [Franco](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) V., [Blazquez](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) J.S., [Ipus](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) J.J., [Law](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) J.Y., [Moreno-Ramirez](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) L.M., [Conde](https://www.sciencedirect.com/science/article/pii/S0079642517301299?via%3Dihub#!) A. Magnetocaloric effect: From materials research to refrigeration devices. Progress in Materials Science, 2018, vol. 93, pp. 112–232. Doi: 10.1016/j.pmatsci.2017.10.005
2. Gschneidner K. A. The Magnetocaloric Effect, Magnetic Refrigeration and Ductile Intermetallic Compounds. Acta Materialia, 2009, vol. 57, pp.18–28. Doi: 10.1016/j.actamat.2008.08.048
3. Val’kov [V.I.,](https://link.springer.com/article/10.1134/S1063783418060343#auth-V__I_-Val_kov-Aff1) Gribanov  [I.F.,](https://link.springer.com/article/10.1134/S1063783418060343#auth-I__F_-Gribanov-Aff1) Todris  [B.M.,](https://link.springer.com/article/10.1134/S1063783418060343#auth-B__M_-Todris-Aff1) Golovchan [A.V.](https://link.springer.com/article/10.1134/S1063783418060343#auth-A__V_-Golovchan-Aff1-Aff2), Mitsiuk [V.I.](https://link.springer.com/article/10.1134/S1063783418060343#auth-V__I_-Mitsiuk-Aff3) Features of Formation of the Magnetocaloric Phenomena in Mn1–tTitAs and Mn1–xCrxNiGe Systems // Physics of the Solid State. 2018. Т. 60. С. 1125-1133.
4. Mitsiuk V.I., Mashirov A.V., Koledov V.V., Valkov V.I., Golovchan A.V., Kovalev O.E., Todris B.M., Pnina Ari-Gur. Magnetic-field-induced transitions and the inverse magnetocaloric effect at liquid helium temperatures in the Mn1‑xCoxNiGe system (0.15≤x<0.80) // JMMM. 2023. Т. 588. p. 171355.
5. Mityuk [V.I.,](https://link.springer.com/article/10.1134/S0031918X22040081#auth-V__I_-Mityuk-Aff1) Rimskii [G.S.,](https://link.springer.com/article/10.1134/S0031918X22040081#auth-G__S_-Rimskii-Aff1) Val’kov [V.I.,](https://link.springer.com/article/10.1134/S0031918X22040081#auth-V__I_-Val_kov-Aff2) Golovchan [A.V.,](https://link.springer.com/article/10.1134/S0031918X22040081#auth-A__V_-Golovchan-Aff2) Mashirov [A.V.,](https://link.springer.com/article/10.1134/S0031918X22040081#auth-A__V_-Mashirov-Aff3) Koledov [V.V.](https://link.springer.com/article/10.1134/S0031918X22040081#auth-V__V_-Koledov-Aff3) Low Temperature Features of the Magnetic and Magnetocaloric Properties of the Mn1–xCoxNiGe System (0.05≤x≤0.4) // Physics of Metals and Metallography. 2022. V. 123. P. 386-391.
6. [Valkov V.I.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=V.&middleName=I.&lastName=Valkov), [Golovchan A.V.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=A.&middleName=V.&lastName=Golovchan), [Gribanov I.F.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=I.&middleName=F.&lastName=Gribanov), [Andreychenko E.P.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=E.&middleName=P.&lastName=Andreychenko), [Kovalev O.Y.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=O.&middleName=Ye.&lastName=Kovalev), [Mitsiuk V.I.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=V.&middleName=I.&lastName=Mitsiuk), [Mashirov A.V.](https://journals.rcsi.science/0015-3230/search/authors/view?firstName=A.&middleName=V.&lastName=Mashirov) Baric Transformation of the Nature of Magnetic Ordering and Magnetocaloric Properties in the Mn1–xCrxNiGe System // Fizika metallov i metallovedenie. 2023. Vol. 124. N. 11. P. 1044-1050.
7. Mitsiuk V. I., Pankratov N. Yu., Govor G. A., Nikitin S. A. Magnetostructural phase transitions in manganese arsenide single crystals // Physics of the Solid State. 2012. V. 54. 1988–1995.
8. Val’kov [V.I.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-V__I_-Val_kov-Aff1) Kamenev [V.I.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-V__I_-Kamenev-Aff1) Golovchan [A.V.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-A__V_-Golovchan-Aff1)   Gribanov [I.F.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-I__F_-Gribanov-Aff1) Koledov [V.V.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-V__V_-Koledov-Aff2) Shavrov [V.G.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-V__G_-Shavrov-Aff2) Mitsiuk [V.I.,](https://link.springer.com/article/10.1134/S1063783421050188#auth-V__I_-Mitsiuk-Aff3) Duda [P.](https://link.springer.com/article/10.1134/S1063783421050188#auth-P_-Duda-Aff4) Magnetic and magnetocaloric effects in systems with reverse first-order transitions // Physics of the Solid State. 2021. Т. 63. №. 12. С. 1889-1899.
9. Mitsiuk V.I., Zhaludkevich A.L., Val’kov V.I. Golovchan A.V., Mashirov A.V., Anikeev S. G., Pikula T., Tkachenka T.M. Magnetocaloric Effect of Zn-Containing Manganese Pnyctides. // Physics of Metals and Metallography. 2024. V. 125. P. 1838-1844.
10. Mitsiuk V.I., Gurbanovich A.V., Gurbanovich An.V., Tkachenka T.M., Valkov V.I., Golovchan A.V., Mashirov A., Surowiec Z. Magnetic and Magnetocaloric Characteristics of the Mn1.9Cu0.1Sb Alloy. // Journal of Communications Technology and Electronics 2023. Vol. 68. P 431–435.
11. Mitsiuk V.I., Govor G.A., Budzyński M. Reversible Phase transitions and magnetocaloric effect in MnAs, MnAs0.99P0.01, and MnAs0.98P0.02 single crystals // Inorg. Mater. 2013. V. 49 P. 14–17.
12. Pankratov N.Yu., Mitsiuk V.I., Ryzhkovskii V.M., Nikitin S.A. Direct measurement of the magnetocaloric effect in MnZnSb intermetalic compound // JMMM. 2019. V. 470. P. 46-49.
13. Govor G.A., Larin A.O., Mitsiuk V.I, Rimskiy G.S., Tkachenkа T.M. Magnetocaloric properties of the single crystal Mn0.99Fe0.01As. // Proceedings of the National Academy of Sciences of Belarus. Рhysics and Mathematics series. 2019. V. 55. P 118–124.
14. Govor G.A., Mitsiuk V.I., Nikitin S.A., Pankratov N.Yu., Smarzhevskaya A.I. Magnetostructural phase transitions and magnetocaloric effect in Mn(As,P) compounds and their composites. // Journal of Alloys and Compounds. 2019. 801. P. 428–437.
15. [Berdiev, U.](https://www2.scopus.com/authid/detail.uri?authorId=57219315612),[Berdiyorov, U.](https://www2.scopus.com/authid/detail.uri?authorId=57768050500),[Toshpulatova, M.](https://www2.scopus.com/authid/detail.uri?authorId=57768293800), [Problems and Tasks of Creating Energy-Saving Electric Machines](https://www2.scopus.com/record/display.uri?eid=2-s2.0-85132979260&origin=resultslist). AIP Conference Proceedings, 2022, 2432, 020002
16. Optimization of the method of oxide coating of metallic iron powder particles Usan Berdiyev, Olga Demedenko, Mirjalol Ashurov, F.F. Hasanov and U.B. Sulaymonov E3S Web Conf., 383 (2023) 04039 DOI: https://doi.org/10.1051/e3sconf/202338304039
17. Bacon G.E., Street R. Magnetic Structure of Manganese Arsenide // Nature 1955. V. 175 P. 518-520.
18. Sirota N.N., Vasilev E.A., Govor G.A. Neutron diffraction study of magnetic and crystallographic phase transformations in manganese arsenide as a function of temperature and pressure // J. Phys. 1971. V. 32 P. 987–989.
19. Ebert H., Kodderitzsch D., Minar J., Calculating condensed matter properties using the KKR-Green's function method-recent developments and applications // Rep. Prog. Phys. 2011. 74. 096501.
20. Research of energy-saving composite materials for electric motors Utkirbek Sulaymonov, Aleksandr Jelutkevich, Malika Nabiyevna, Oybek Sayfullayev and Ulug’bek Berdiyorov E3S Web Conf., 461 (2023) 01054 DOI: https://doi.org/10.1051/e3sconf/202346101054
21. Vosko S.H., Wilk L., Influence of an improved local-spin-density correlation-energy functional on the cohesive energy of alkali metals // Phys. Rev. 1980. B. 22. P. 3812-3815.
22. Liechtenstein A.I., Katsnelson M.I., Antropov V.P., Gubanov V.A., Local spin density functional approach to the theory of exchange interactions in ferromagnetic metals and alloys // JMMM 1987. Vol. 67. P. 65-74.
23. Use of composite alloys for two stator-valve electric motors Usan Berdiyev, Utkirbek Sulaymonov and Zilola Mirakhmedova E3S Web Conf., 461 (2023) 01081 DOI: https://doi.org/10.1051/e3sconf/202346101081
24. Amirov, O. Boltaev, K. Shakenov, F. Akhmedova, O. Kutbidinov. Determination of induced voltages on lines with complex approach trajectories. AIP Conf. Proc. November 4, 2025; 3331 (1): 030096. <https://doi.org/10.1063/5.0305935>
25. O. Boltaev, Sh. Sharapov, V. Mammadov, F. Akhmedova, S. Khakimov. Investigation of transducer modes with an excitation screen and scattering parameters. AIP Conf. Proc. November 4, 2025; 3331 (1): 040052. <https://doi.org/10.1063/5.0305985>
26. O. Boltaev, G. Tokpeissova, F. Akhmedova, O. Kutbidinov. Mathematical modeling of electromagnetic effects of the traction system on the adjacent line. AIP Conf. Proc. November 4, 2025; 3331 (1): 040022. <https://doi.org/10.1063/5.0305764>